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Title: Can supershear transition be seen in damage and aftershock pattern? Part one: Theory

Author(s): Bruhat, Lucile; Jara, Jorge; Antoine, Solene; Okubo, Kurama; Thomas, Marion Y.; Rougier, Esteban; Rosakis, Ares J.; Sammis, Charles; Klinger, Yann; Jolivet, Romain; Bhat, Harsha S.

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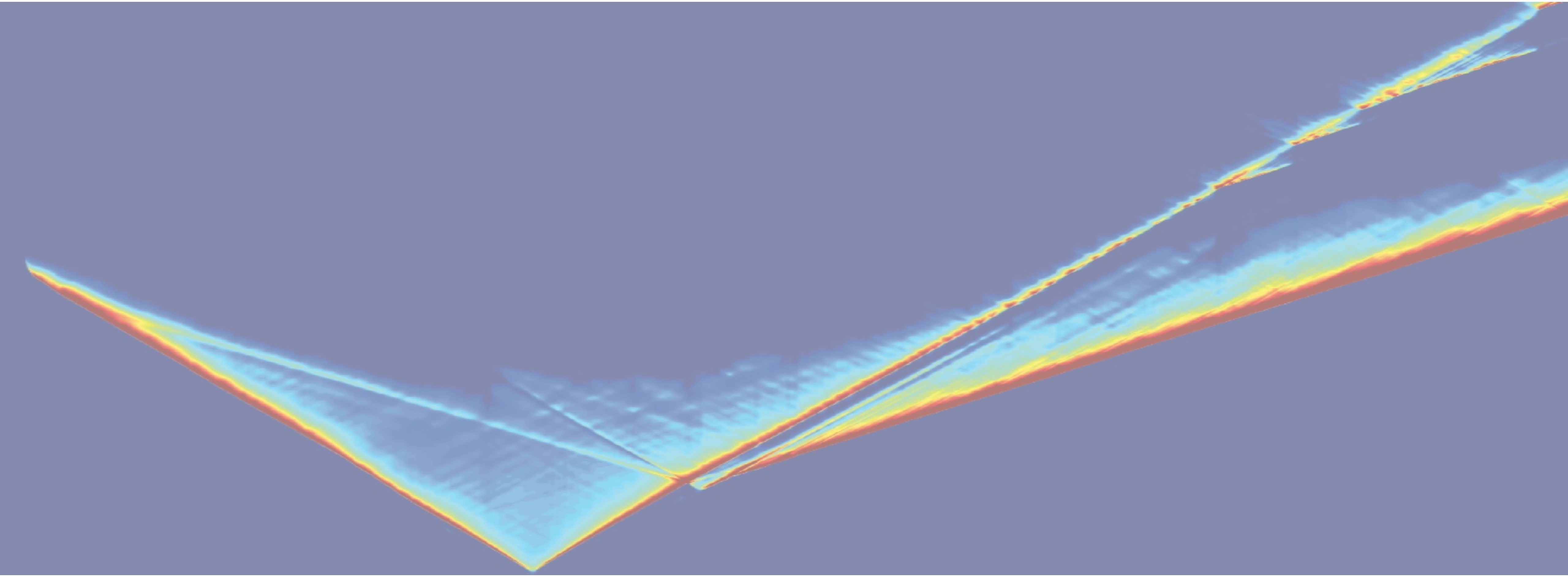
Can supershear transition be seen in damage and aftershock pattern?

Part one: Theory

Lucile Bruhat, J. Jara, S. Antoine, K. Okubo, M.Y. Thomas,
E. Rougier, A. J. Rosakis, C. Sammis, Y. Klinger, R. Jolivet & H.S. Bhat



What are the conditions for transitioning supershear?

As shown by Michel Bouchon, supershear ruptures are rare events

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In practice….

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In practice….

Associated with linear, narrow fault segments by field studies [Bouchon, et al., 2010]

- ➢ Homogenous stress-strength conditions ?

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BUT Supershear rupture can develop when the rupture propagates from a region of high strength to a region of low strength [Dunham, 2007, Liu and Lapusta, 2008]

- Heterogeneous stress-strength conditions ?

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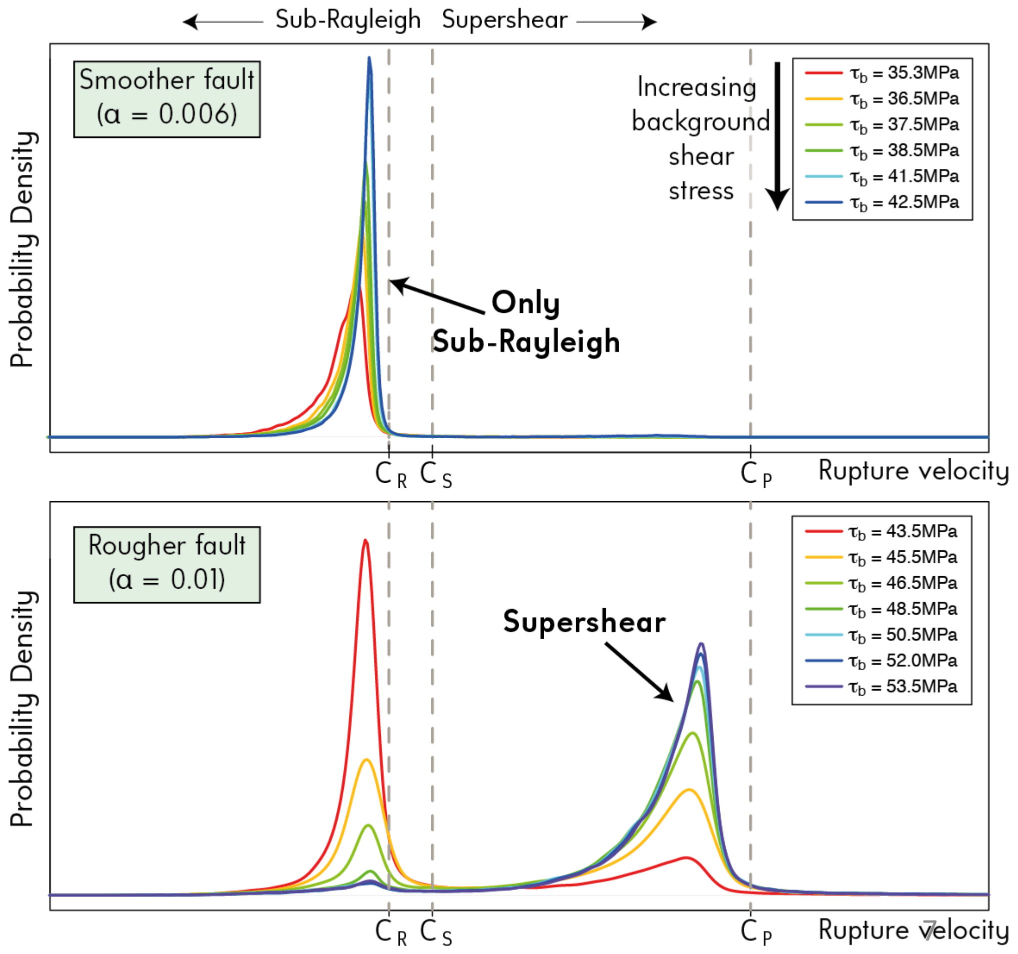
- ➢ Heterogeneous stress-strength conditions ?

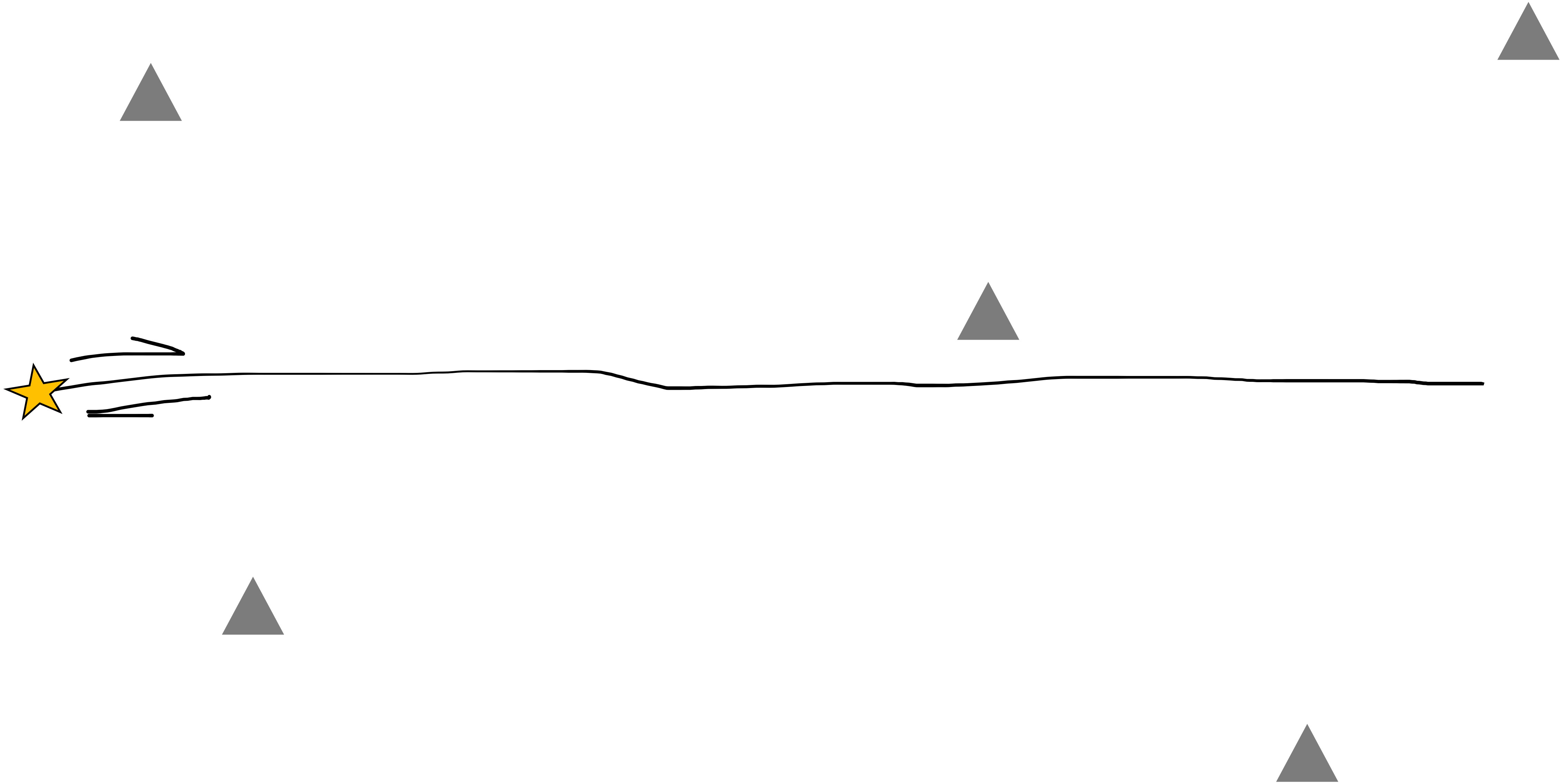
Example from looking at rough faults

- Supershear transients are more likely on rough, i.e. non planar faults
- Supershear is observed even at low background shear stress (outside the classical Burridge-Andrews range)



[Bruhat, et al. 2016]

So what is the sticking point here?



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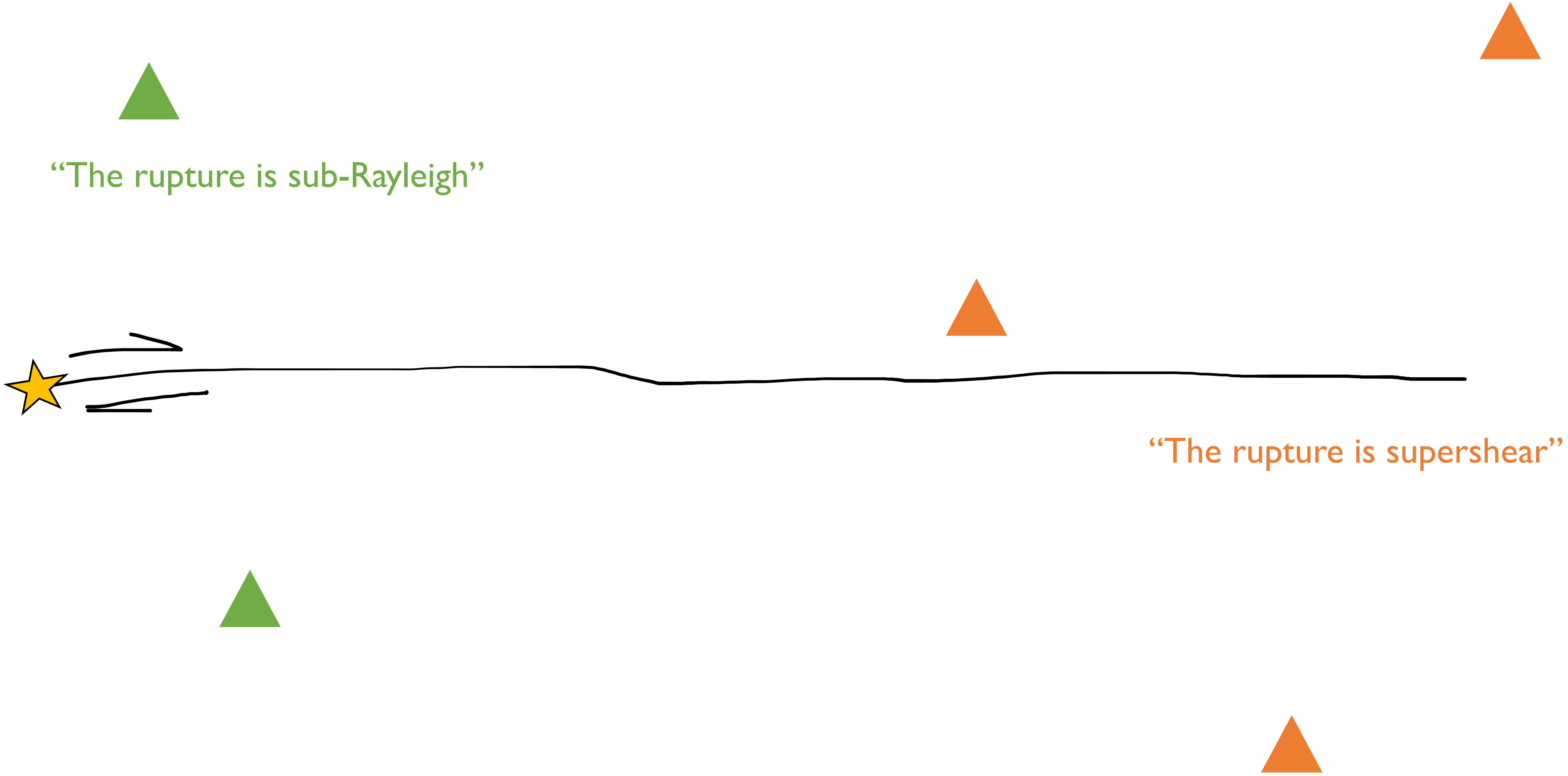

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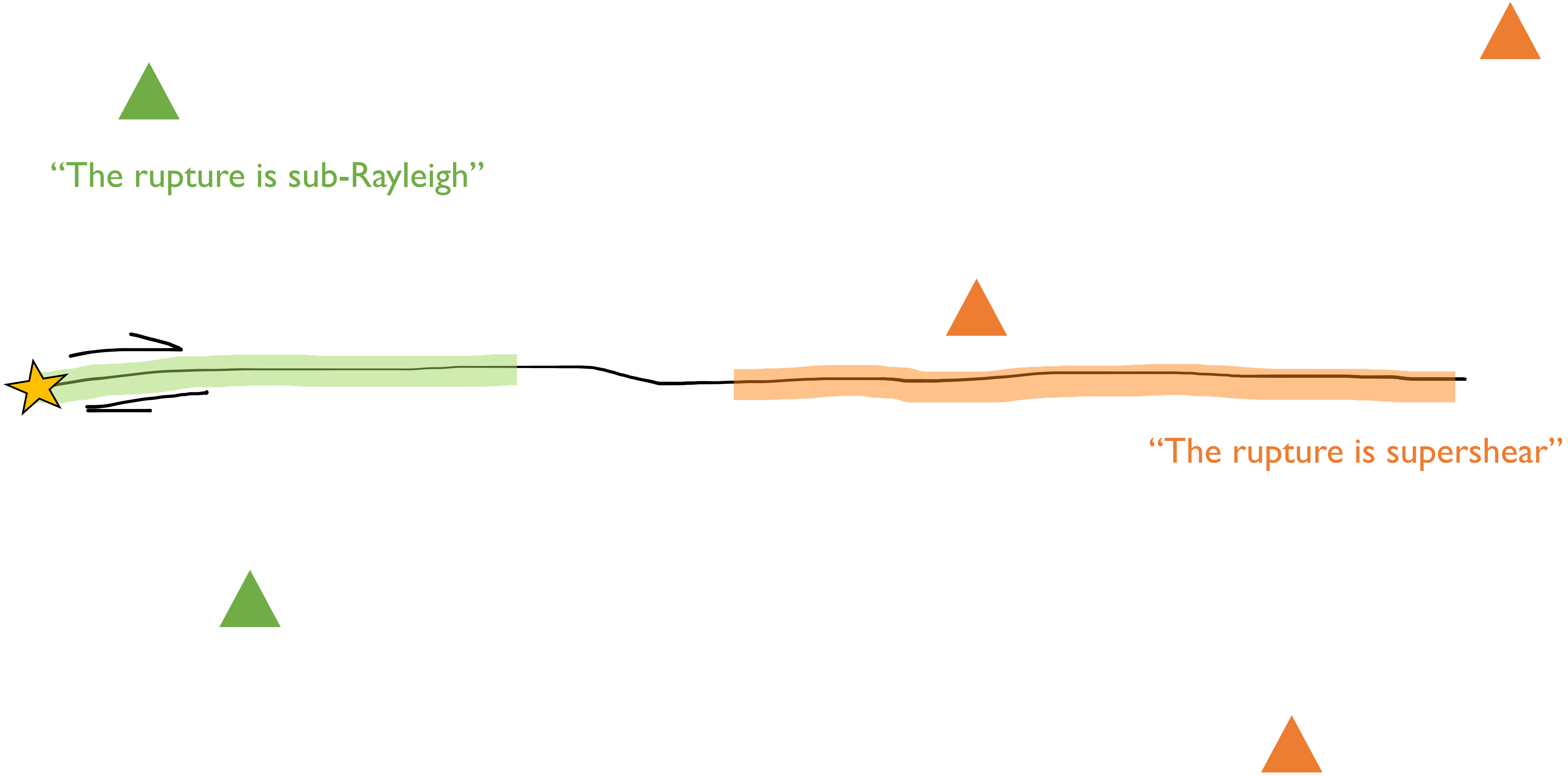

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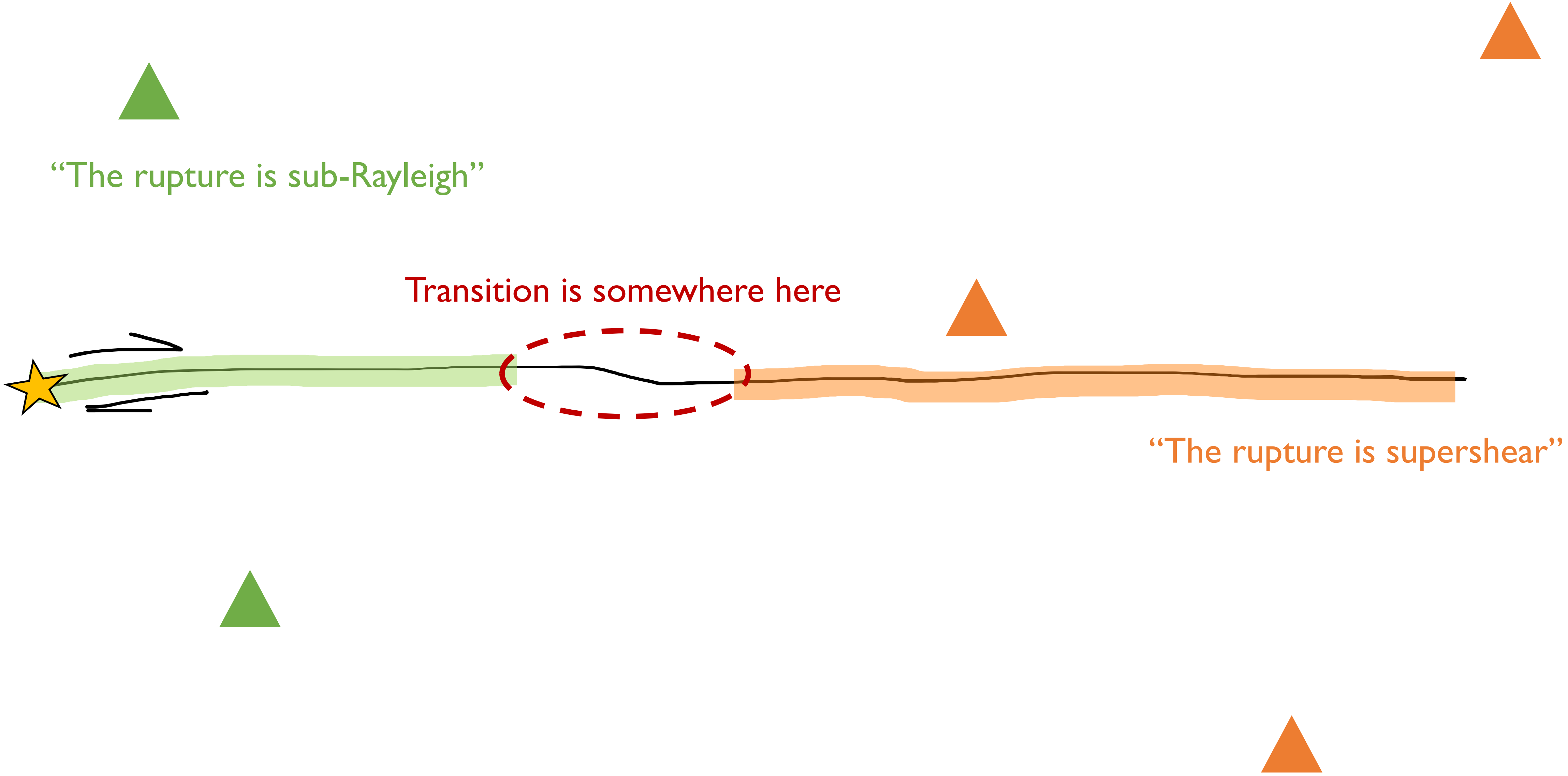

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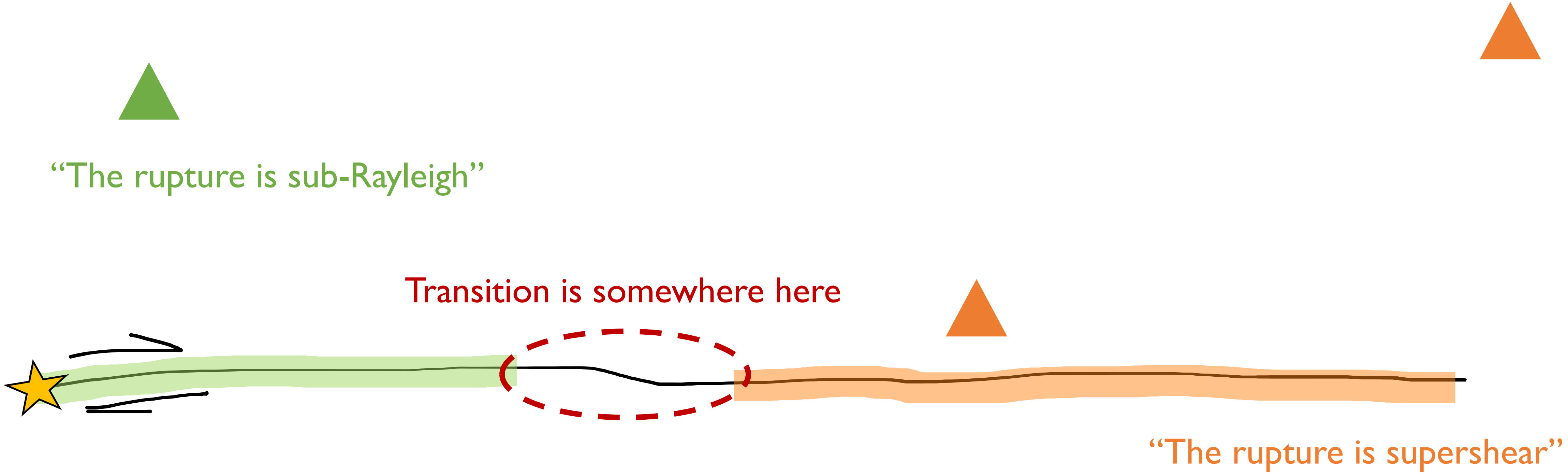
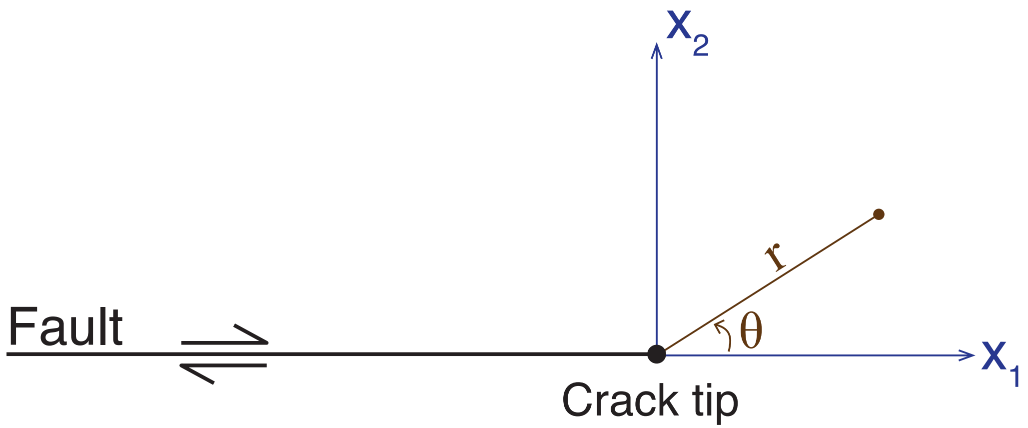


- Observational studies focus on the <u>well-developed</u> part of the supershear rupture, a vague location of the transition is deduced <u>a posteriori</u>
- Numerical studies focus on generating that transition <u>without knowing what are the actual field conditions are for the transition</u>

- **Need for a physics-based method to locate the transition sub-Rayleigh/supershear**

What is the stress intensity at the crack tip?

Solutions to describe the state of stress around a crack tip using Linear Elastic Fracture Mechanics (LEFM) [Williams, 1957, Freund, 1979].



$$\sigma_{\alpha\beta}(r,\theta) = \frac{K_{II}}{\sqrt{2\pi r}} f_{\alpha\beta}^{II}(r,\theta)$$

Semi-infinite plain-strain crack in a 2D homogeneous isotropic linear medium

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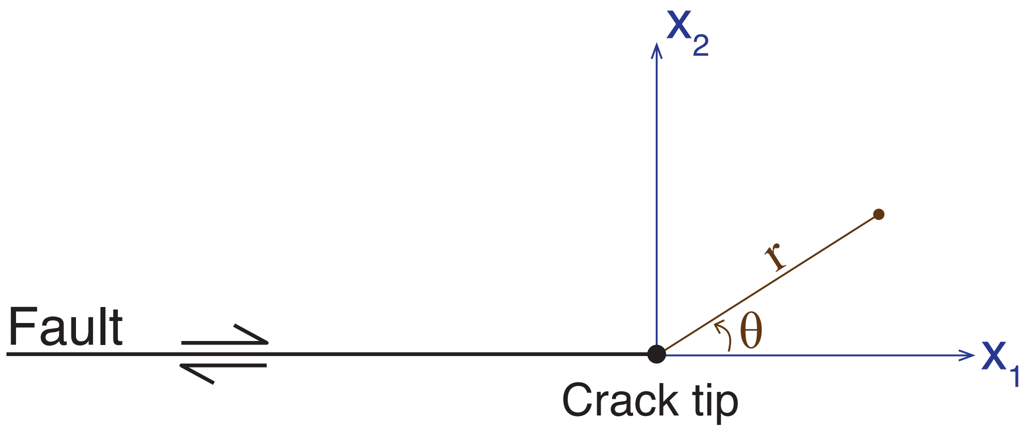

Stress at a point around the crack tip

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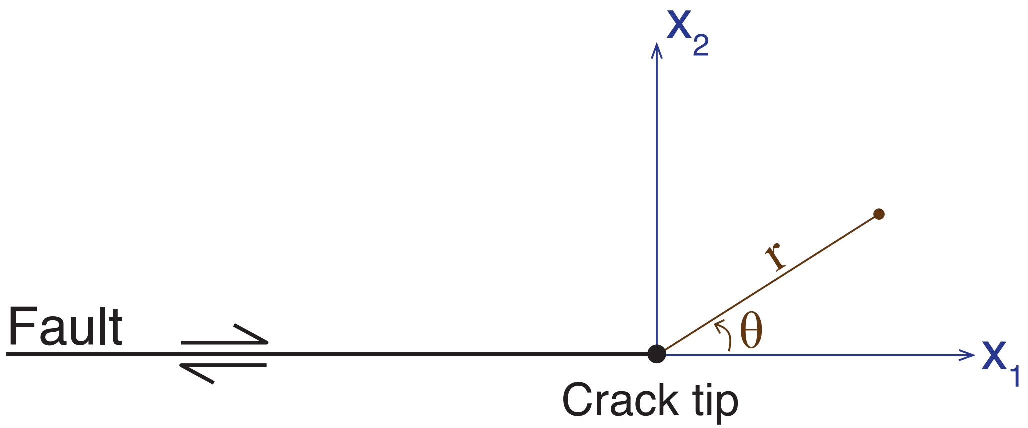

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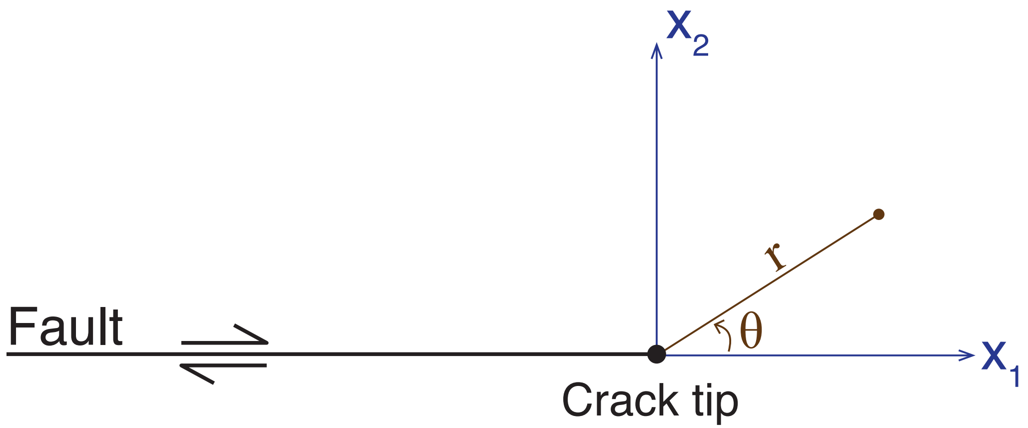

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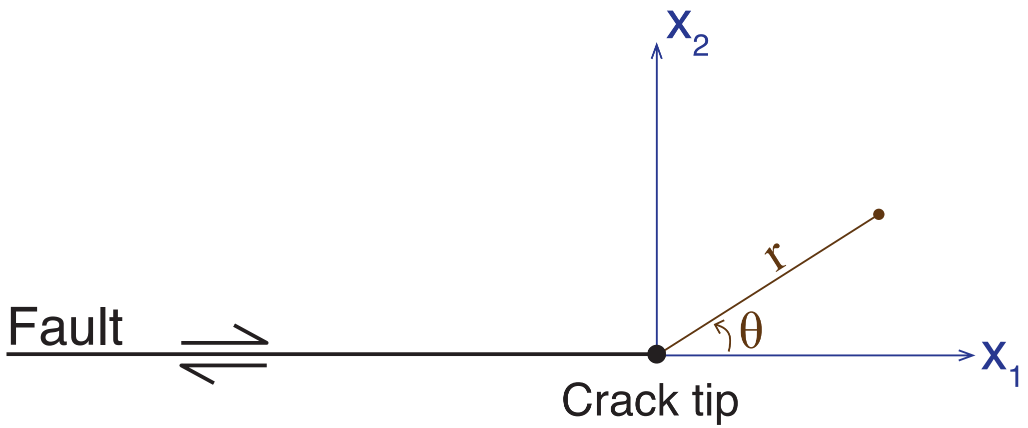

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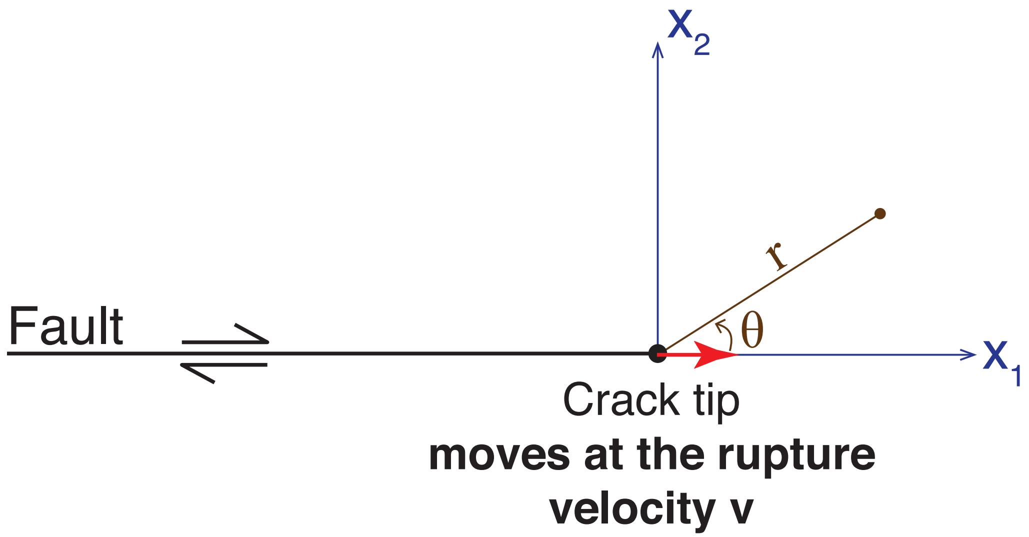
For reference $K_{II} = \Delta\tau\sqrt{\pi L}$

where $\Delta\tau$ the stress drop and L the crack length

Now, let the rupture move at a speed v

Due to the moving coordinate system, all the fields undergo a Lorentz-like contraction, affecting both the stress intensity factor K and the angular function f



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$$\sigma_{\alpha\beta}(r,\theta,v) = \frac{K_{II}^{dyn}}{\sqrt{2\pi r}} f_{\alpha\beta}^{II}(r,\theta,v)$$

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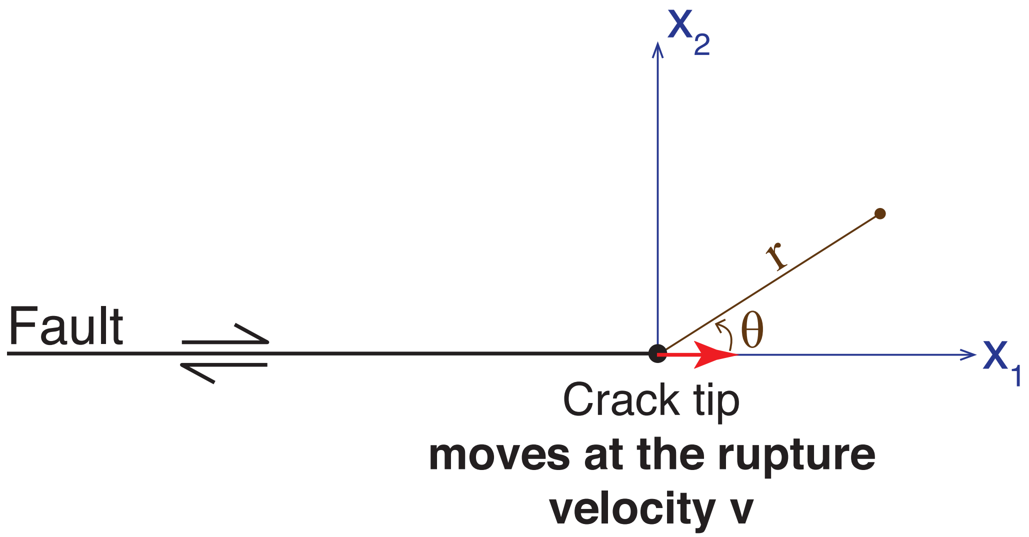

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For a rupture propagating at speed v < c_R

$$K_{II}^{dyn} \approx \frac{1 - v/c_R}{\sqrt{1 - v/c_P}} K_{II}$$

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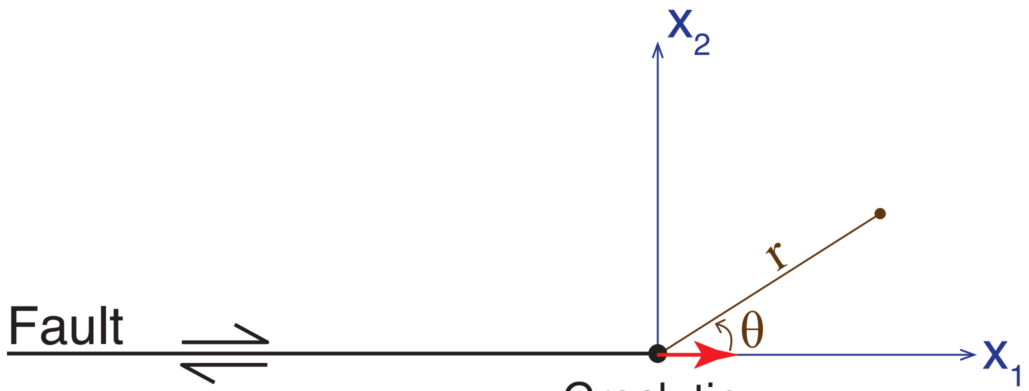

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As $v \to c_R$,
$K_{II}^{dyn} \to 0$
$\sigma_{\alpha\beta} \to 0$

The stress concentration will shrink with increasing speed !

Stress intensity at the crack tip controls the extent of off-fault damage

Classical Drucker-Prager failure criteria to compute the extent of the yield region (region where damage is allowed)

$$r_{DP}(\theta, \nu, f) = (K_{II}^{dyn})^2 A(\theta, \nu, f, F)$$

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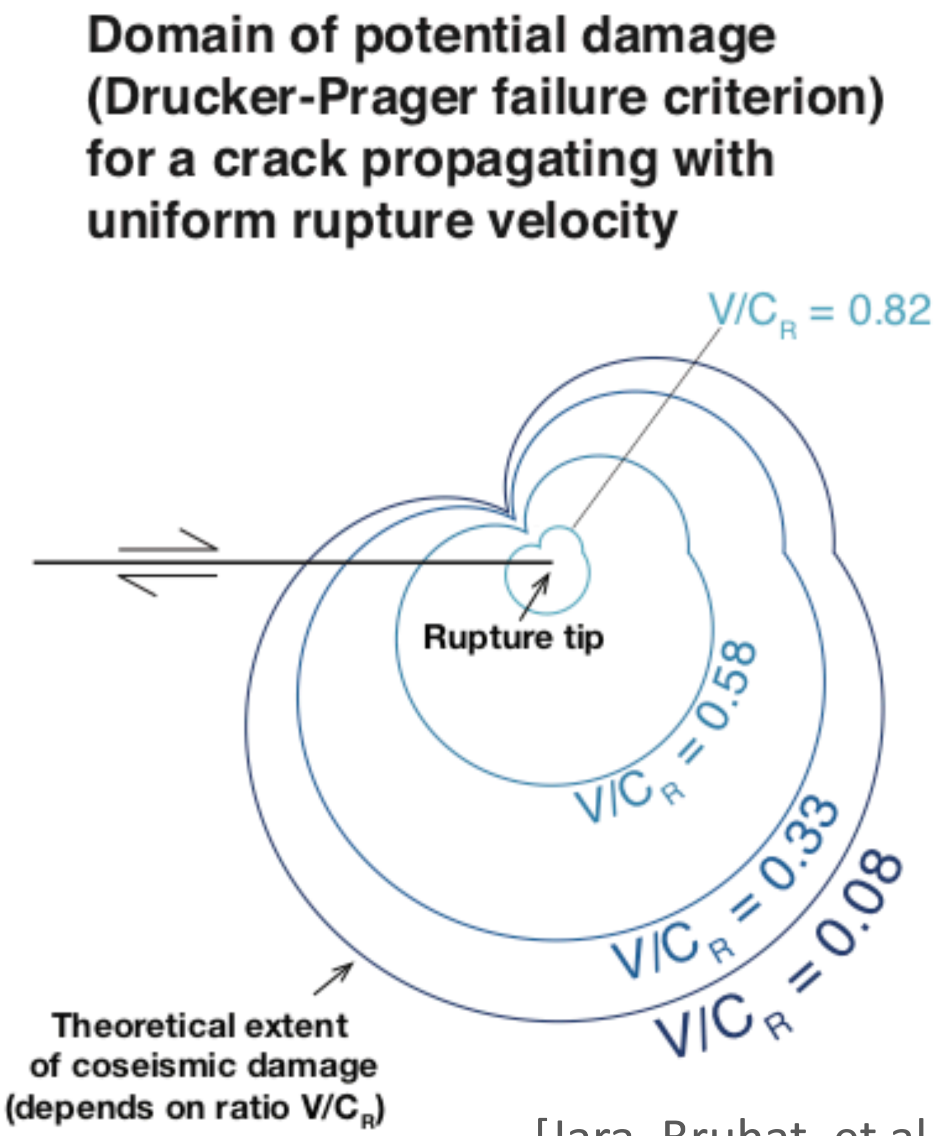
Increases with the crack length L

Decreases with increasing speed v

Stress intensity at the crack tip controls the extent of off-fault damage

Extent of the damaged region

- Decreases with increasing speed v

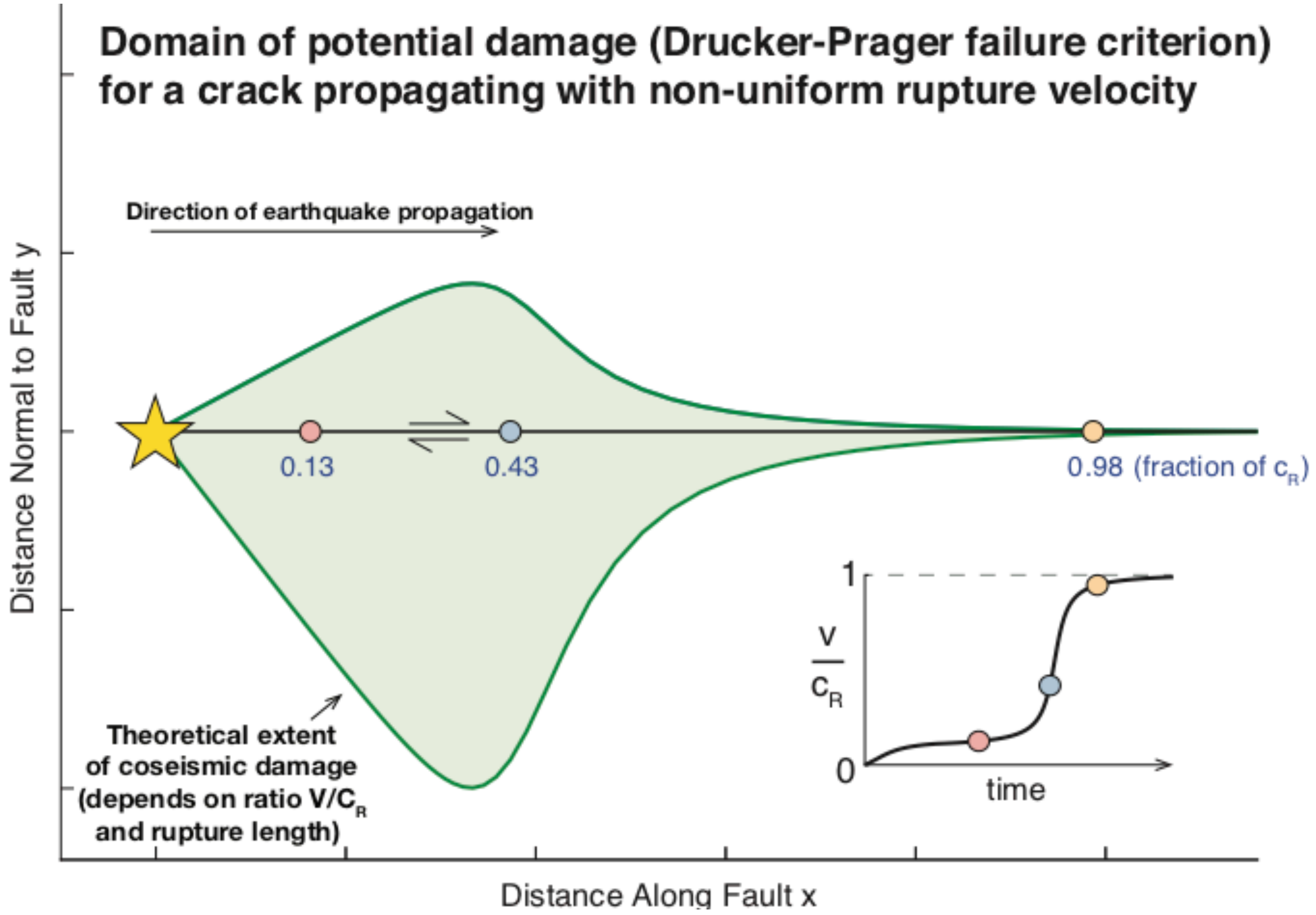


[Jara, Bruhat, et al., submitted]

Stress intensity at the crack tip controls the extent of off-fault damage

Extent of the damaged region

- ➢ Decreases with increasing speed v
- ➢ Increases with crack length L



[Jara, Bruhat, et al., submitted]

What could it mean for supershear transition?

Theoretical method valid when the rupture is sub-Rayleigh $v < c_R$

But, to transition to supershear, the rupture has to first bypass c_R!

We expect to see shrinkage of the near-fault damage zone at the transition sub-Rayleigh/supershear

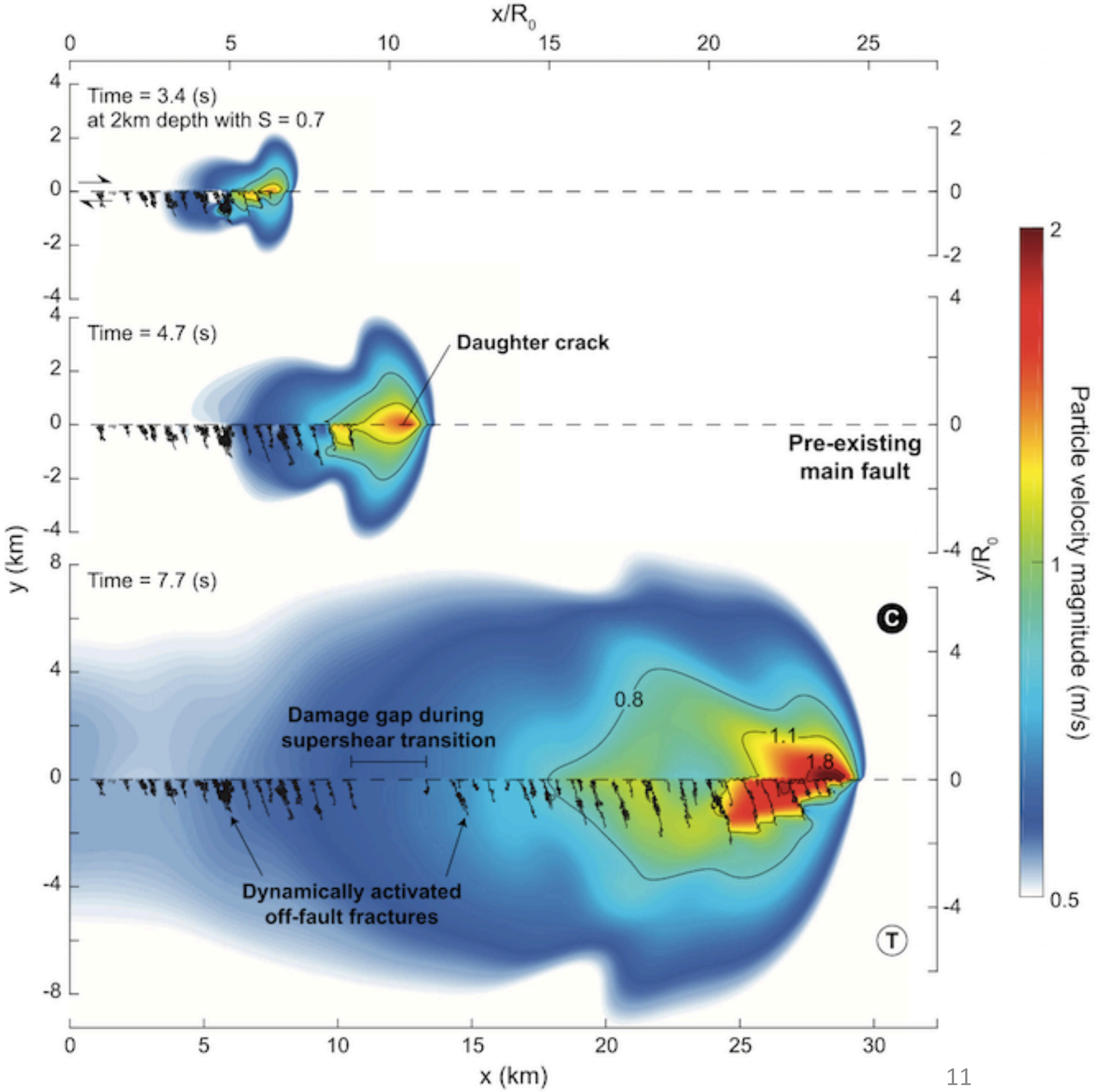
→ Verification using two numerical codes for dynamic rupture and damage generation

FDEM numerical methods [Okubo, et al., JGR, 2019]

- Combined Finite-Discrete Element Method (FDEM) to produce dynamically activated off-fault fracture networks [Rougier, et al. 2016]

- During sub-Rayleigh, extent of the off-fault fracture zone grows linearly with the rupture propagation.

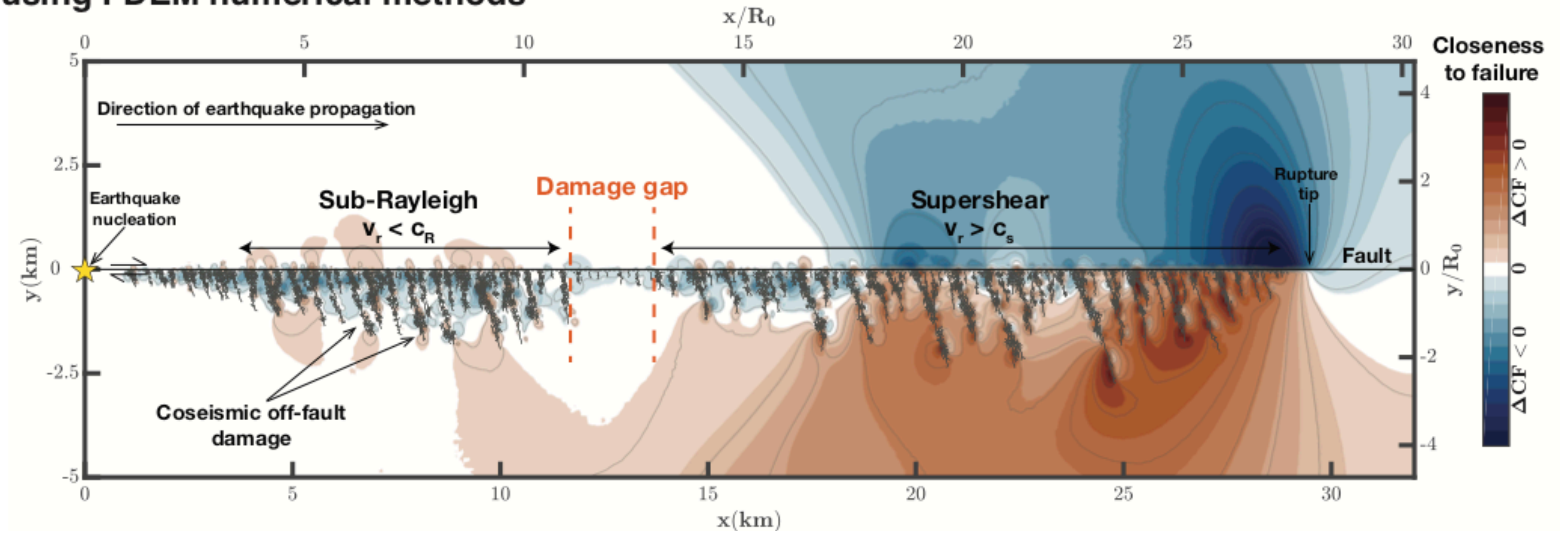
- Spatial extent of the off-fault damage zone drops dramatically when transitioning to supershear regime



[Okubo, et al., JGR, 2019]

FDEM numerical methods [Okubo, et al., JGR, 2019]

Closeness to failure and coseismic off-fault fracture pattern of a supershear transition using FDEM numerical methods

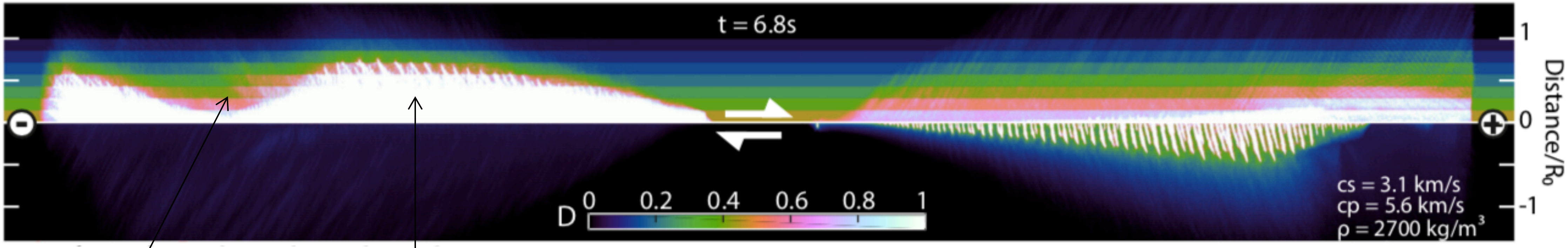


[Jara, Bruhat, et al., submitted, using the method developed in Okubo, et al., JGR, 2019]

Micromechanics approach [Thomas & Bhat, GJI, 2018]

- Reflects the micro-physics of damage evolution by relating damage density to the near-tip stress state and by computing the corresponding dynamic changes of elastic properties in the medium due to the presence of newly formed cracks.

- Sudden shrinkage of the damage zone during the supershear transition



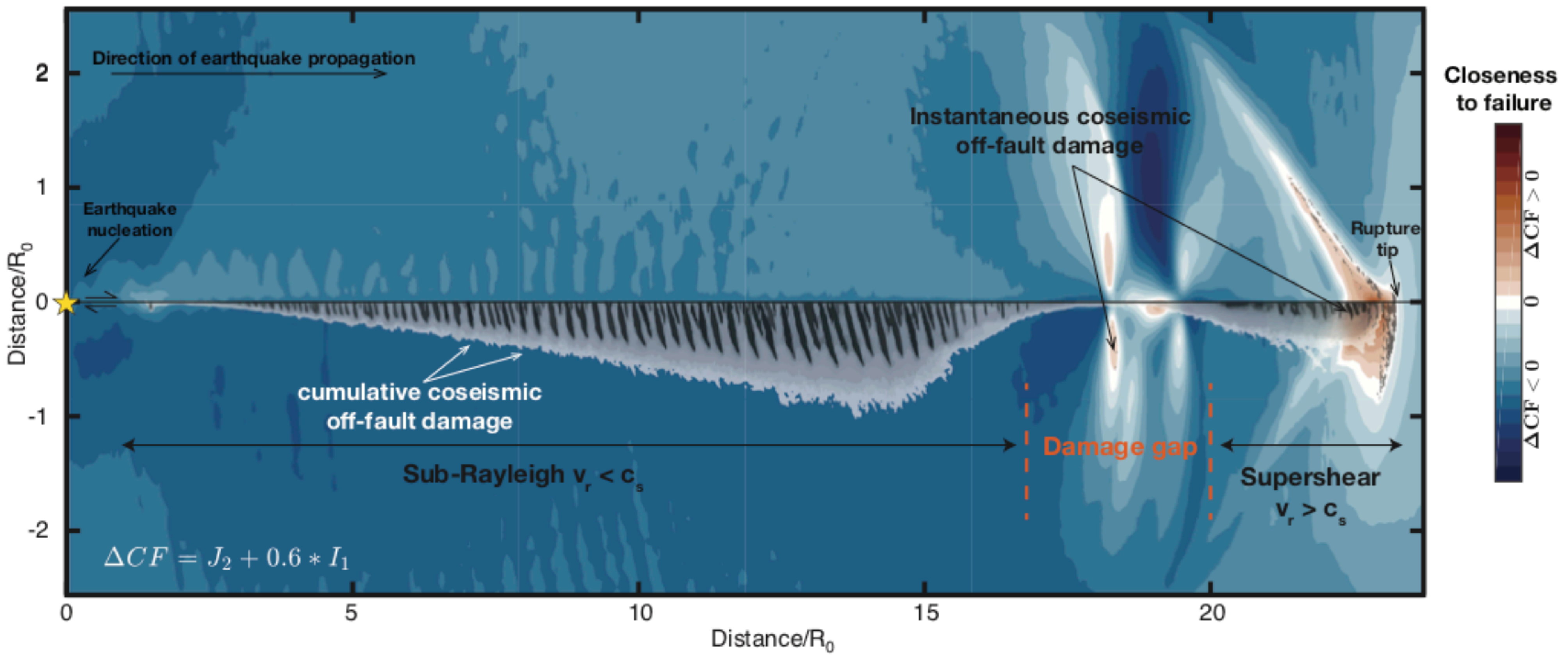
Damage extent

Region of supershear transition

[Thomas & Bhat, GJI, 2018]

Micromechanics approach [Thomas & Bhat, GJI, 2018]

Closeness to failure and damage pattern of a supershear transition using a homogenized law for microcracks



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What we've learned from fracture mechanics and numerical modeling

- Stress intensity at the crack tip evolves with the rupture velocity
- As the rupture velocity approaches the Rayleigh wave speed, before transitioning to supershear, the stress intensity reduces
- As a result, the region affected by the stress intensity decreases in size as well, leading to a sudden shrinkage of the near-fault damage zone

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IS THIS REAL?